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The Metallurgist

Supplement to The Engineer, *February, 1939*

Research in the Iron and Steel Industry

IN 1927 the late Mr. S. M. Gluckstein read a paper before the Institute of Chemistry in which he gave an account of the development of the chemical staff and laboratories of J. Lyons and Co., Ltd., illustrating the value of the applications of science in a large industrial undertaking. Later, an annual Memorial Lecture was endowed by the scientific staff of the company with the broad intention of obtaining periodic reviews of the application of science in various branches of industry and of the economic importance of scientific research to the community. In the course of nine years, distinguished lecturers have dealt with different aspects of the subject, but none has followed more closely the lines intended by the original founders of the lectureship than Dr. W. H. Hatfield, F.R.S., who delivered the Tenth Lecture last December on the subject "Research in the Iron and Steel Industry."*

This result was achieved partly because Dr. Hatfield kept in the foreground the idea that the industrial research worker, though generally not absorbed in the financial aspect of things, must be alive to the manufacturing and commercial interests of the organisation that he serves.

Apart from historical allusions to the older literature and technical development of the industry and an account of the formation of societies and institutions and of the rise of the applied science departments of the universities, the lecture has a wide general interest in tracing out the main lines of scientific advance in the twentieth century which have contributed to the progress of metallurgy. But to the metallurgist its chief value will be that it is the best account hitherto available of the organisation of the collective research of the iron and steel industry, which is carried out under the ægis of the Iron and Steel Industrial Research Council, which is recognised as the research association of the industry by the Department of Scientific and Industrial Research.

The collective research, as is well known, is carried out by the aid of committees voluntarily set up within the framework of the Research Council organisation by the scientific and technical representatives of individual firms of the industry. A list of these committees is reproduced on the following page, as their scope may not always be fully realised. Dr. Hatfield gives cogent reasons for preferring this method of working, in the special circumstances which characterise the iron and steel industry, to the formation of a central research body with laboratories and a scientific staff acting for the industry as a whole. There will always be differences of opinion about these two methods. Carried out by the Committee method the work may lack some coherence and continuity, but it gains in the width of experience from which it derives, not only ideas for, but actual prosecution of scientific research work. It is, however, in a special degree essential to the success of the collective research method that every individual firm interested should maintain a scientific staff capable of understanding and applying the results of such research. Dr. Hatfield quotes a very effective comment made by Mr. H. H. Burton: "The idea that scientific work can be broadcast without the existence in each firm of a suitable individual or body of scientific men to interpret the results, is similar to broadcasting music in the absence of individual receiving sets properly tuned to the necessary wave length." Such an organisation governed in size by the needs of the firms in question is common throughout the industry. Research carried out by the staff of different firms still forms by far the largest part of the total research activity in the field of iron and steel, but much of the work affecting the technical efficiency of the industry as a whole has lost its "independent" character, and has become "co-operative" in fulfilment of the settled policy of the Federation. Nevertheless, the immediate industrial demands on the manufacturers' laboratories continue undiminished, and Dr. Hatfield indicates how these demands are met by describing the organisation of the Brown-Firth research laboratories. It is a feature of such research laboratories throughout the industry that, while they are primarily designed for the improvement of the processes and products of the manufacturing companies which support them, all their facilities are made available for the solution of the problems of the users of the companies' products—another form of co-operative investigation which has proved to be of the greatest importance in opening up new fields of application of standard materials and in directing the course of development of new products.

It is extremely useful to have so concise and authoritative an account of the iron and steel research organisation in the development of which Dr. Hatfield himself has done invaluable service.

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RESEARCH IN THE IRON AND STEEL INDUSTRY

Committees of the Iron and Steel Industrial Research Council.

- Structure of Alloys Advisory Committee
  - Steel Castings Committee
    - Moulding Sands Committee
    - Foundry Practice Sub-Committee
  - Alloy Steels Committee
    - Thermal Treatment Sub-Committee
    - Hair-line Crack Sub-Committee
- High Temperature Research
  - Corrosion Committee
    - Low Alloy Steels Sub-Committee
    - Protective Coatings Sub-Committee
    - Laboratory Research Committee
    - Marine Corrosion Committee
    - Alloy Steels (Corrosion) Committee
    - Soil Corrosion Sub-Committee
- Iron and Steel Institute (Services)
  - Steel Ingots (Heterogeneity) Committee
    - Liquid Steel Temperatures Sub-Committee
    - Oxygen Panel
    - Ingot Moulds Sub-Committee
  - Library, Bibliographic, Abstracts and Publishing Services, Service to Joint Committees
  - Technical Information, Editorial, and Printing Services, Service to Committees
  - Standardisation
- British Iron and Steel Federation, Tchical Department
  - Blast-furnace Committee
    - Midland Coke Committee
    - Northern Coke Committee
    - Scottish Coke Committee
    - Coke Co-ordination Committee
    - Scientific Panel
    - Blast-furnace Practice Sub-Committee
    - Blast-furnace Reactions Committee
    - Blast-furnace Slag Tests Panel
    - Blast-furnace Refractories Panel
    - Field Tests Panel
- Steel Sheet Research Committee
  - Open Hearth Committee
    - Instruments Sub-Committee
    - Refractories Committee
    - Gas Producer Committee
  - Rolling Mill Committee
    - Furnaces Committee
    - Instruments Committee
    - Roll Design Committee
    - Production Studies
- Local Research Committees:
  - South Wales Siemens Steel Committee
  - Welsh Plate and Sheet Manufacturers' Research Committee
  - Industrial Furnaces Committee
  - Sheffield and Rotherham Smoke Abatement Committee

Strain Markings in Aluminium Alloys

SOME interesting photomicrographs of strain markings in several different types of aluminium alloy have recently been published by M. Bosshard and H. Hug.[1] Stress distribution figures analogous to those produced by the Fry etching of overstrained mild steel were developed by W. Roth[2] in homogenised and cold-worked magnesium-aluminium alloys by annealing at 100 deg. to 150 deg. Cent., and etching to develop the grain structure. Zones of high stress-concentration were delineated by dark lines due to precipitation of Mg_2Al_3 accelerated by the cold work. Even at an advanced stage of heat treatment the precipitation processes are, according to E. Ruppel,[3] affected by previous cold working, though not after reheating at 150 deg. and 175 deg. Cent. This phenomenon in the 5 per cent. copper alloys was investigated in greater detail by W. L. Fink and D. W. Smith,[4] and used by them to explain the double peaks in the ageing curve of these alloys. They showed that quenching in cold water produced plastic deformation, and argued that since plastic deformation accelerates the rate of precipitation, local deformation at grain boundaries and slip planes would result in the precipitation reaching a maximum in these regions before it reached a maximum in the body of the grains. Microscopical evidence supported the view that precipitation occurred first along the slip planes of specimens which had been quenched in cold water (without any subsequent working), but if the quenching was in boiling water or in oil no slip bands were produced, indicating the absence of internal strain, and uniform precipitation took place throughout the grains. The chief interest of Bosshard and Hug's paper is that they show that the phenomenon is of general occurrence in a range of commercial alloys (Table I).

TABLE I.—*Percentage Composition of Alloys which Showed Strain Markings.*

	Cu.	Mg.	Mn.	Si.	Ni.	Ti.
Peraluman 7	—	6·8	0·45	<0·3	—	0·1
"BA" alloy	—	3·5	0·5	<0·3	—	—
Avional D	3·8	0·55	0·5	<0·3	—	—
Avional 88	4·3	1·4	1·4	0·5	—	—
Avional Z	4·5	0·8	0·7	0·5	—	—
"Y" alloy	4·0	1·5	—	<0·3	2·0	—

The conditions under which it was observed varied with composition. Precipitation on the gliding planes was evident in the 7 per cent. magnesium alloy which had been cold worked 20 per cent. after homogenising and before ageing for ten days at

100 deg. Cent. The same effect occurred in the 3·5 per cent. magnesium alloy, but about 50 to 70 per cent. cold work was found to be necessary to produce the most striking result. No localised precipitation was observed in the copper-magnesium-aluminium

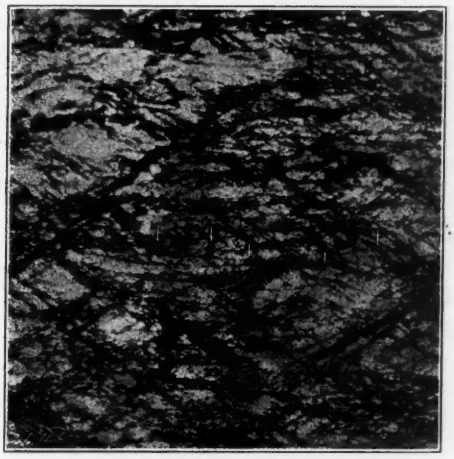

FIG. 1—*Peraluman 7, Homogenised, Cold Worked 50 per Cent. and heated for Ten Days at 100 deg. Cent. Magn. 300. Etched with 9 per Cent. H_3PO_4.*

alloys after 20 per cent. reduction by rolling. In Avional D it was first observed after 40 per cent. cold rolling had been applied. The alloy was quenched in water from 500 deg. Cent., cold worked by various amounts, and heated for twenty-four

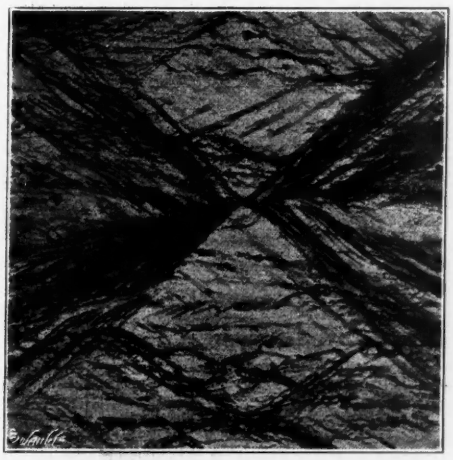

FIG. 2—*Avional Z, Quenched from 500 deg. Cent., Cold Worked 78 per Cent., and Heated Twenty-four Hours at 160 deg. Cent. Magn. 150. Etched with $NaF+HCl+HNO_3$.*

hours at 160 deg. Cent. After similar treatment with reheating at temperatures up to 200 deg. Cent., strain figures were also evident in the other alloys mentioned in Table I. In magnesium-silicon-aluminium alloys (Anticorodal) strain figures have hitherto not been observed, but with a suitable etching reagent this may be possible later. The reagents used by Bosshard and Hug were 9 per cent. phosphoric acid for the magnesium-aluminium alloys and diluted Keller's solution for the others. Keller's solution consists of 1 c.c. HF (conc.), 1·5 c.c. HCl (conc.), 2·5 c.c. HNO_3 (conc.), and 95 c.c. water; the specimen is immersed for ten to twenty seconds and washed in warm water. As used by Fink and Smith the composition was modified to 0·5 gr. NaF, 1 c.c. HCl (conc.), 2 c.c. HNO_3 (conc.) per 100 c.c. of solution. Bosshard and Hug also used sodium fluoride. Typical micrographs are shown in Figs. 1 and 2.

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[1] *Metallwirtschaft*, 1938, 17, 708.
[2] *Zeit. Metallkunde*, 1936, 28, 288.
[3] *Metallwirtschaft*, 1937, 16, 1307.
[4] *Metals Technology*, 1937, 4, Techn. Pubn. No. 865.

The Effect of Arsenic on Steel

AN important and comprehensive study of the influence of arsenic on the properties of carbon and alloy steels has been published by E. Houdremont, H. Bennek, and H. Neumeister.[1] Reference may, however, first be made to a summary of published information by F. Körber and G. Haupt[2] which forms an excellent basis from which to consider the newer work. A bibliography (from 1864 to 1936) on the influence of arsenic on the properties of iron and steel was published by the Iron and Steel Institute[3] in 1937, and a selection from this is given, but Körber and Haupt have also assembled many numerical data with a critical comparison and assessment of their value. The final conclusions of the authors were as follows :—

In static tensile tests arsenic has no detrimental effect up to 0·3 per cent. According to J. Liedgens and M. J. Marchal, the tensile strength increases up to 2 per cent. arsenic and then diminishes. The hardness of steels is hardly affected by arsenic up to 0·78 per cent. (a conclusion somewhat inconsistent with the above statement). The impact figure falls with increase of arsenic in the region studied, up to 0·46 per cent. There is divergence of opinion as to its effect on bend tests. J. E. Stead found bend tests still to be good at 1 per cent. of arsenic, but F. W. Harbord and H. E. Tucker placed the limit at 0·19 per cent. arsenic. According to J. O. Arnold 1·57 per cent. arsenic in pure iron brings about a considerable reduction of the capacity for bending. In rolling experiments there was no clear indication of the deterioration of rolling properties with increase of arsenic. In Harbord and Tucker's experiments, the worst value was at 0·23 per cent.; steel with 0·35 per cent. was better. A. E. Cameron and G. B. Waterhouse found no red-shortness in steel with 4 per cent. arsenic. J. Liedgens observed it first at 2·8 per cent. arsenic. Both were consistent with the statement by G. Lüdogowskij and N. Dübin that with up to 0·4 per cent. of arsenic steel is neither hot-short nor cold-short. High-speed steel shows diminishing efficiency as the arsenic increases to 0·8 per cent. The limit of arsenic beyond which mild steel cannot be forge welded is given by different observers at 0·1, 0·15, and 0·27 per cent. Autogenous welding may be applied up to 3·5 per cent.

arsenic, and electric resistance welding up to 2·8 per cent. The rusting of mild steel is retarded by arsenic. An increased tendency to form hardening cracks was observed with increase of arsenic up to 0·35 per cent. in a 1 per cent. carbon steel. By the use of transformer sheets containing 0·5 to 1·0 per cent. arsenic, electrical losses are greatly reduced. In cast iron the effect of arsenic is to decrease the tensile strength, increase the hardness, and reduce the resistance to impact. The transverse strength first shows a decrease when arsenic exceeds 1 per cent. Wear increases up to 0·32 per cent. arsenic and then diminishes. Corrosion resistance to acids and alkalis is increased.

Though this collection of data is useful, it lacks the coherence of the strictly comparable tests carried out on carefully prepared series of steels by Houdremont, Bennek, and Neumeister. These steels were made in 25-kilo. melts in a high-frequency furnace. The types are indicated in Table I. They were referred to by a letter, and a number indicating the arsenic content in 0·01 per cent., *e.g.*, B 102 is type B with 1·02 per cent. arsenic. The arsenic was added as the element, wrapped in sheet metal, and pushed under the molten steel. All the steels of group A were killed with 0·1 per cent. of aluminium in the ladle. All casts were forged without difficulty into bar or plate, and no red-shortness was observed even with the highest arsenic content.

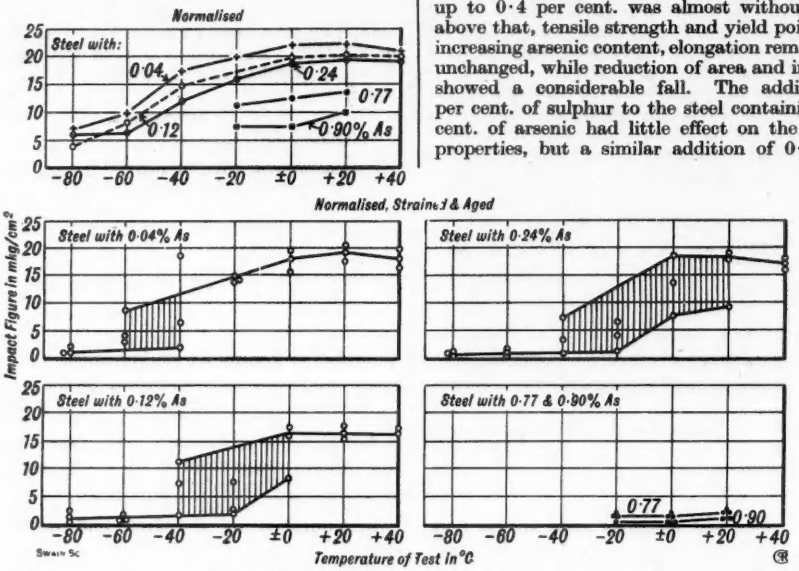

FIG. 1—*Influence of Arsenic Content on the Impact Figure/temperature Curve of Carbon Steel Containing About 0·15 per cent. Carbon in the Normalised and Strain-aged Condition (Specimens 10 mm. by 10 mm. by 55 mm. with 2 mm. Diameter Notch, 3 mm. Deep)*: (I) *Normalised Half an Hour at 920 deg. Cent.*; (II) *Normalised Half an Hour at 920 deg. Cent., Strained 10 per cent., Reheated Two Hours at 250 deg. Cent., and Cooled in Air.*

MECHANICAL PROPERTIES.

Mild Steel A.—The test specimens were taken from normalised 20 mm. diameter bar. Arsenic up to 0·4 per cent. was almost without influence; above that, tensile strength and yield point rose with increasing arsenic content, elongation remained almost unchanged, while reduction of area and impact figure showed a considerable fall. The addition of 0·1 per cent. of sulphur to the steel containing 0·25 per cent. of arsenic had little effect on the mechanical properties, but a similar addition of 0·1 per cent. of phosphorus to the steel containing 0·16 per cent. of arsenic markedly raised the yield point and tensile strength, increased the grain size, and brought down the reduction of area and impact figure to lower values than they would have reached with six times the amount of arsenic alone. The ageing properties were greatly affected by arsenic content as is clearly shown by Fig. 1. In spite of the aluminium treatment, the steels with 0·77 and 0·90 per cent. of arsenic, which had impact values of 13 mkg. and 10 mkg. per square centimetre at 20 deg. Cent. in the normalised condition, had fallen to a very low figure after strain-ageing.

Medium Carbon Steel B.—The ingots were forged to 20 mm. diameter bar; material for the test specimens was quenched in water at 820 deg. Cent.,

TABLE I.—*Types of Steel Made in the Laboratory High-frequency Furnace.*

Type.	Steel.	Per cent. C.	Per cent. Si.	Per cent. Mn.	Per cent. Cr.	Per cent. Ni.	Per cent. Mo.	Per cent. As.
A	Mild steel	0·14	0·25	0·60	—	—	—	0·04 to 0·90
B	Medium carbon steel...	0·46	0·30	0·75	—	—	—	0·04 to 1·02
C	Ni-Cr heat treatable ...	0·33	0·30	0·55	0·75	3·70	—	0·04 to 1·31
D	Cr-Mo heat treatable...	0·33	0·30	0·60	1·10	—	0·23	0·02 to 0·18
E	Heat-resisting Cr-Mo...	0·16	0·30	0·45	0·88	—	0·47	0·04 to 0·41
F	Weldable Cr-Mo ...	0·25	0·25	0·45	1·05	—	0·20	0·02 to 1·24
G	Carbon tool steel ...	0·95	0·35	0·80	0·07	—	—	0·02 to 1·16

Sulphur and phosphorus each about 0·02 per cent., except for one high sulphur and one high phosphorus mild steel.

tempered for half an hour at 500 deg. or 600 deg. Cent., and cooled in air or in a furnace. In all these conditions the yield point and tensile strength (in spite of some irregularities) were not much affected by arsenic up to 1 per cent. The elongation was almost unchanged. The reduction of area showed a clear diminution with increasing arsenic content, and the fall was already unmistakeable with 0·15 per cent. of arsenic. It was more pronounced in the series

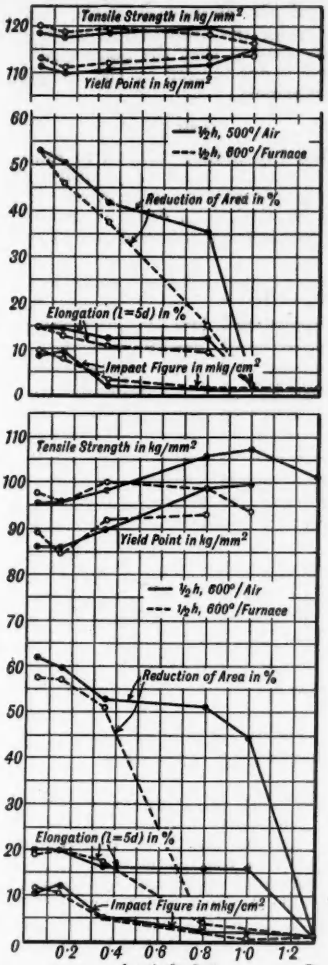

FIG. 2—*Influence of Arsenic on the Strength Properties of Nickel-Chromium Steel, Oil Hardened from 820 deg. Cent. and Tempered (Specimens 10 mm. by 10 mm. by 55 mm. with 2 mm. Diameter Notch, 3 mm. Deep).*

tempered at 500 deg. Cent. Impact figures declined slightly in steels with high arsenic content.

Nickel-Chromium Steel C.—Specimens of the steel in the form of 20 mm. diameter bar were oil-hardened from 820 deg. Cent., tempered at 500 deg. or 600 deg. Cent. for half an hour, and cooled in air or in the furnace. Up to 1 per cent. of arsenic there was a rise in yield point and tensile strength which was more evident in the steels tempered at 600 deg. Cent. than in the harder specimens. The ductility values were lowered by the addition of arsenic to a greater extent than in the carbon steels (Fig. 2). This was specially so with reduction of area. The impact figure was unchanged up to 0·15 per cent. of arsenic and then fell. The elongation, which was unaffected by arsenic in carbon steels, showed a marked fall when the arsenic exceeded 0·8–1·0 per cent. The steel with 1·3 per cent. of arsenic was so brittle that it broke prematurely with practically no elongation or reduction of area. The steels were considerably worse in this respect after slow cooling, though the impact figures were already so low that slow cooling made little difference.

Chromium-Molybdenum Steel D.—These steels were also oil hardened as 20 mm. diameter bar from 820 deg. Cent., tempered at 500 deg., 600 deg., or 720 deg. Cent. for half an hour, and cooled either in air or in the furnace. There was no appreciable change in properties in the range examined, viz., 0·04 to 0·18 per cent. of arsenic.

Chromium-Molybdenum Creep-resisting Steel E.—The yield point, maximum load, and elongation of these steels remained unaltered when the arsenic content rose from 0·04 to 0·41 per cent. The impact value showed a tendency to temper brittleness when a treatment involving slow cooling or prolonged heating was applied.

Carbon Tool Steel G.—The influence of arsenic on hardenability and susceptibility to overheating was determined. The casts were forged to bar 30 mm. in diameter and were oil hardened together from 850 deg. Cent. to put them into a comparable initial condition. They were then water quenched from 740 deg., 760 deg., 780 deg., 820 deg., and 840 deg. Cent. The Ac_1 point was raised from 725 deg. with 0·02 per cent. of arsenic to 745 deg. with 1·16 per cent. of arsenic. The high arsenic specimens were not fully hardened in quenching from 740 deg. Cent. Fractures showed that arsenic has no effect on depth of hardening up to 0·2 per cent. Beyond that, depth of hardening diminishes with increasing arsenic content. Moreover, the hardened zone loses its velvety appearance and becomes matt grey while the core shows a sharp edged brittle fracture instead of the tough fibrous appearance of the low-arsenic steels. An increase in susceptibility to overheating set in at about 0·2 per cent. of arsenic.

RESISTANCE TO CORROSION

Tests on mild steels containing 0·04, 0·18, and 0·24 per cent. of arsenic in conductivity water, in an industrial atmosphere and in acid vapour, failed to establish any marked effect of arsenic either in improving or lessening corrosion resistance.

PICKLING OF STEELS CONTAINING ARSENIC

With the object of determining the conditions under which arseniuretted hydrogen would be formed during pickling, tests were made on mild steels containing 0·04, 0·18, and 0·90 per cent. of arsenic, in the form of strip 0·5 mm. thick and 40 mm. wide. These were first heated for three hours at 800 deg. Cent. to produce scale on the surface. The specimens were then pickled in 1 : 10 sulphuric acid at 60 deg. Cent. with and without the addition of a restrainer. The gases evolved from the pickling bath used without a restrainer readily gave an arsenic mirror. Those evolved when a restrainer was used showed no arsenic mirror in half an hour even when the steel contained 0·90 per cent. of arsenic. The poisonous AsH_3 only appeared when the iron itself was attacked

and was not formed until the descaling was completed. The pickling liquids containing a restrainer were found to be free from arsenic even when they had served to descale specimens containing up to 0·90 per cent. of arsenic.

RESULTS OF WORKS EXPERIMENTS

In order to test the effect of arsenic on a larger scale a 20-ton basic Bessemer melt was made of mild steel containing 0·24 per cent. of arsenic. It was cast into four ingots, one of which was forged to billets, another rolled to sheet, and another sectioned for examination. The sectioned ingot showed no features to distinguish it from an arsenic-free ingot. Analysis at various places showed that the segregation of arsenic was similar in character and extent to that of phosphorus. Mechanical tests were made on sheets 1 mm. and 12 mm. thick, and, for comparison, tests were made on similar material without arsenic. The steels did not differ in tensile strength and yield point, or in elongation, or in the results of Erichsen tests. On the other hand, the influence of arsenic was clearly evident in the impact figures, which are collected together in Fig. 3. In the upper range of temperatures (above 0 deg. Cent.), the impact figure of the steel containing arsenic was somewhat lower than that of the arsenic-free steel. The region of scatter occurred at about the same temperature in each steel, but at a higher temperature in the specimens from the head of the ingot, thus confirming the view that the combined influence of arsenic and phosphorus was more pronounced than that of arsenic alone.

The behaviour on cold drawing and the resultant mechanical properties were not affected by 0·24 per cent. of arsenic, but the electrical resistance of the wire was increased by 10 per cent. Adhesion of a zinc deposit to the steel was unaffected by the presence of arsenic. Numerous welding tests were made with different methods of welding. It was concluded that though there was a slight decrease in weldability, the results were so good that steel with 0·24 per cent. of arsenic could be said to meet all present-day demands. The deleterious effect of 1·24 per cent. of arsenic was very pronounced.

By the open-hearth process a steel containing carbon 0·29, manganese 1·07, and arsenic 0·23 per cent. was made, and a similar steel without arsenic. One of the 46 cm. square ingots of each steel was sectioned longitudinally, etched and sulphur printed, and an analysis taken of specimens from twenty-two places in each ingot. In killed steel the arsenic was found to segregate about as much as the carbon, phosphorus, and sulphur. In unkilled steel the segregation resembles that of phosphorus. Mechanical properties of the normalised steels, and also the behaviour under the drop test of axles made from both steels, showed that the good quality of steel of this type is not injured by the presence of 0·23 per cent. of arsenic.

REMARKS

While the two papers referred to form excellent summaries—the one based on published researches, and the other directly on experiment—of the effect of arsenic on steel, it is desirable not to overlook the very compact summary of previous work and valuable original investigation contained in the paper on "The Effect of Arsenic in Steel," published by A. E. Cameron and G. B. Waterhouse[4] in 1926. There is little in the recent work that contradicts anything found by these authors, though naturally a considerable amount which supplements it; in particular there is the note of caution which is sounded by the observed deterioration in the properties of the high-grade heat-treated alloy steels when much arsenic is present, an effect which first makes itself evident in reduction of area and impact figure. The arsenic present in ores and other materials charged into the blast-furnace will practically all be reduced and enter the pig iron. The arsenic present in the pig iron and other materials used in the manufacture of steel will all enter the steel. Hence steel scrap in the course of years tends to become enriched with arsenic as it also is with copper and nickel. A certain amount of segregation producing a banded structure in the steel has also to be reckoned with. There is, therefore, no doubt as to the importance of such investigations as those reviewed in the present article. For the most part the results are

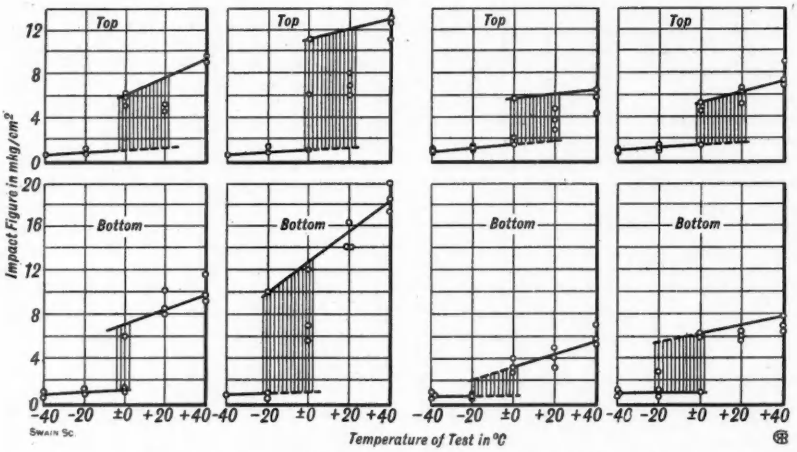

FIG. 3—*Impact Figures of Normalised, 12 mm. Thick, Basic Bessemer Steel Sheets with 0·02 and 0·24 per cent. Arsenic (Specimens 10 mm. by 10 mm. by 55 mm. with 2 mm. Diameter Notch, 3 mm. Deep).*

reassuring in relation to quantities of arsenic likely to be present as an accidental impurity, but the influence of small quantities of arsenic in special alloy steels intended for use in a high-tensile condition demands further investigation.

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[1] *Archiv für das Eisenhüttenwesen*, 1938–39, 12, 81; also *Tech. Mitt. Krupp*, July, 1938, 101.
[2] *Ibid*, 1938–39, 12, 91.
[3] Iron and Steel Institute, Bibliographical Series, No. 4, 1937.
[4] *Journal*, Iron and Steel Institute, 1926 (1), 113, 355.

The Solubility of Hydrogen in Aluminium Alloys

ATTEMPTS on the part of several investigators to determine the solubility of hydrogen in pure aluminium led for many years to very discordant results. This was due to unsatisfactory methods of determining the solubility and to difficulties associated with the oxide film present on the surface of both liquid and solid aluminium and with the high rate of diffusion with which hydrogen can pass through a quartz tube at the temperatures involved in the experiments. J. Czochralski[1] passed hydrogen through the molten metal at various temperatures and determined the solubility by the change of density of the rapidly solidified metal. The change, due to the presence of internal cavities, was thought to give a measure of the amount of gas liberated on solidification. Such a method affords little more than a qualitative comparison of the amounts of hydrogen required to saturate the metal at different temperatures. In methods depending on absorption or evolution of the gas at constant temperature very long times are required to ensure equilibrium conditions. After twenty hours in contact with hydrogen the molten metal is still absorbing hydrogen very slowly, though the times for attainment of equilibrium may be reduced if the molten metal is stirred.[2] A. Sieverts and W. Krumbhaar[3], as long ago as 1910, came to the conclusion that hydrogen was not soluble in solid aluminium. This was apparently confirmed by several investigators[4] who found that no diffusion of hydrogen through aluminium occurs at any temperature below the melting point. These results, however, were probably due to the oxide film. D. Alekseev and L. Savinina[5] found that hydrogen electrodeposited on an aluminium cathode will diffuse through the aluminium very easily, although molecular hydrogen will not diffuse through an aluminium sheet. On the other hand, C. J. Smithells and C. E. Ransley[6] found that hydrogen will diffuse at a measurable rate through aluminium at temperatures above 400 deg. Cent. The rate of diffusion was greatest for a surface freshly scraped in hydrogen and decreased to one-tenth of the initial rate after some hours. There is therefore some slight solid solubility of hydrogen in aluminium; nevertheless, it remains true that hydrogen is practically insoluble in the solid metal. The most reliable results available for the solubility of hydrogen in liquid aluminium are those of L. L. Bircumshaw[7], who obtained the values:

	C.c. per 100 gr.
At 700 deg. Cent.	0·23
800 „ „	0·89
900 „ „	1·87
1000 „ „	3·86

These agreed closely with the values obtained by P. Röntgen and H. Braun,[8] and by P. Röntgen and F. Möller.[9] The latter authors found that hydrogen had no measurable solubility in solid aluminium just below its melting point, but recorded a sudden jump to 0·22 c.c. per 100 grammes in molten metal.

Recent work by W. Baukloh and F. Oesterlen[10] was undertaken in order to determine the solubility of hydrogen in various aluminium alloys, and to serve as a basis of comparison the solubility of hydrogen in pure aluminium was redetermined. The method used involved direct volume measurements of the absorption of hydrogen by a given volume of the metal or alloy (weights ranging from 70 to 80 grammes) which had previously been degassed at 950 deg. Cent. and cooled *in vacuo*. (The alloys containing magnesium received their degassing and cooling in an atmosphere of argon.) Precautions were taken against the diffusion of hydrogen through quartz by the use of a double-walled tube, hydrogen being contained in the annular space at a pressure equal to that within the tube. The molten metal in the sintered corundum boat was not stirred in any way, the period found to be necessary for adjustment to equilibrium conditions was 1½ to 2 hours, and the final readings were not taken until the volume had been constant for thirty minutes. The curve obtained by Baukloh and Oesterlen for the solubility of hydrogen in pure aluminium, and used by them as a basis for comparing the effect of alloy additions, lay considerably above Bircumshaw's (1935) values, to which no reference was made. Baukloh and Oesterlen's curve shows:—

	C.c. per 100 gr.
At 700 deg. Cent.	1·0
800 „ „	1·7
900 „ „	2·8

They found no solubility in solid aluminium, but a jump at the melting point of 0·6 c.c. more than that found by Röntgen and Möller.

The effect of the alloy additions may be briefly summarised as follows:—

Copper.—The hydrogen solubility diminished with increase in copper. The 6 per cent. alloy showed a very much lower solubility than its neighbours (5·5 and 8·3 per cent.). Apart from this, the fall in solubility was regular with increase in copper, dropping to about one-third at 700 deg. or one-half at 900 deg. Cent. in the 14 per cent. copper alloy.

Silicon.—The solubility was diminished irregularly in the series of silicon alloys containing 6, 11·4, and 19·8 per cent. of silicon.

Manganese.—All the alloys containing up to 3·7 per cent. manganese showed some solubility in the solid state, but only the 2·8 per cent. showed a higher liquid solubility than pure aluminium.

Nickel.—Again, all three alloys (0·66, 0·87, and 1·39 per cent. of nickel) showed some solubility in the solid state, but all except the 0·66 per cent. alloy showed a lower solubility in the molten alloy than in aluminium.

Magnesium.—All specimens had a distinctly higher solubility for hydrogen than is shown by pure aluminium. It is evident, however, that very different conclusions might be drawn from data given for the alloys containing 5 per cent. and 6 per cent. of magnesium, though it seems most unlikely that their real behaviour should be different. The following values derived from the curves are of interest in this connection:—

Magnesium, per cent.	C.c. per 100 gr. at— 600 deg. Cent.	700 deg. Cent.	800 deg. Cent.
0	Nil	1·0	1·7
5	0·3	1·2	1·8
6	0·9	3·0	3·6
9	0·2	0·8	2·4

There is no indication in the paper as to the

accuracy with which duplicate results could be obtained, and it may be wise to draw no more than general conclusions, ignoring the minor fluctuations in the values. The discrepancies between Baukloh and Oesterlen's estimate of the solubility of hydrogen in pure aluminium and the more generally accepted values of Bircumshaw and of Röntgen and his co-workers leave some uncertainty as to whether even the comparative values of the results may not be affected by differences in the condition of the surface film on alloys of different compositions.

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Magnesium Alloys: Applications and Future Development

No. I

DURING the last few years few metallurgists and engineers can have failed to have had their attention drawn to the very remarkable properties of magnesium and its alloys, the consumption of which is continually increasing. A general and informative account of the present position and future development and application of these alloys has been given by E. Lay, of Frankfurt-a.-M.[1] What makes this relatively new material so attractive to all users of metals is its very low specific gravity, good mechanical strength properties, excellent machinability, resistance to alkali attack, and other properties. On the other hand, it has properties which are disadvantageous such as limited resistance to corrosion and sensitivity to acids, a rather low capacity to be cold worked at room temperatures, a considerable affinity for oxygen, and evidence of notch sensitivity. However, its good properties stand so much to the fore that as a result magnesium consumption not only in Germany, but outside that country, is growing steadily.

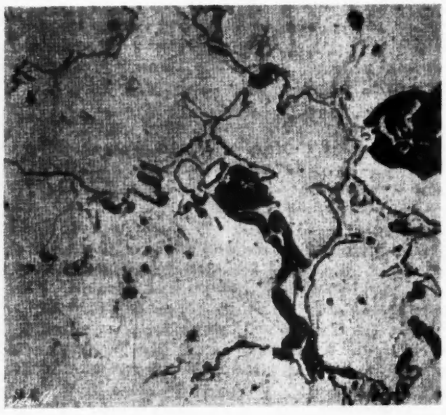

FIG. 1—*9 per cent. Aluminium-Magnesium-Alloy, as Cast.*

Pure magnesium is of itself of little importance as a constructional material compared with its alloys. It is being used in Germany for electrical conductors, and from a weight point of view its conductivity compares favourably with that of aluminium.

Numerous suggestions for new alloys and for their introduction have been made, but of these only a relatively small number have resulted in alloys of industrial importance. The magnesium alloys of industrial importance mainly contain additions of aluminium, manganese, zinc, and silicon. In special cases, additions of silver, cadmium, and other metals have been proposed.

The casting alloys have achieved considerably greater importance than the hot-worked alloys, such as sand castings, die castings, and pressure die castings, for the reason that no further working is necessary and since the mechanical properties compare favourably with aluminium casting alloys when the specific gravity is taken into account. Magnesium alloys have found extensive application for moving parts such as for aeroplane engines and fuselage, for omnibuses and lorries, in automatic machines especially for parts which must be moved very often by hand, in leather, shoe and textile machines, &c.

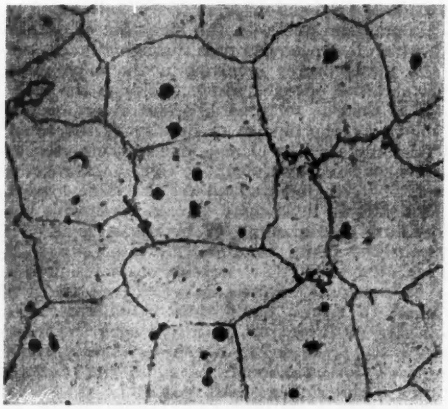

FIG. 2—*Homogenised.*

The properties of the magnesium alloys most widely used in Germany to-day are given in Table I, together with the strongest aluminium alloys and grey cast iron for comparison. Magnesium alloys of the magnesium-aluminium group containing 8 to 9 per cent. aluminium are subjected mostly to a heat treatment consisting of an annealing or homogenising operation alone or together with subsequent temper hardening. Alloys of this group are made use of in the form of sand and die castings. The homogenised condition is obtained by at least twenty-four hours' annealing in stages at about 390 deg. to 410 deg. Cent. in an atmosphere of SO_2, or in a bichromate bath, followed by rapid cooling. Fig. 1 shows the micro-structure of the alloy in the cast state; Fig. 2 that of the same material after having been given the homogenising treatment. If the alloy is not heated in stages as described above, but is brought

by continuous heating to the upper limit of the temperature, then melting occurs of the $MgAl_2$ constituent. The mechanical strength and appearance of the fracture is thereby impaired since insufficient opportunity had been given for diffusion to take place during the heating. For the temper-hardening treatment, the homogenised components are heated for eight to ten hours at 180 deg. to 190 deg. Cent. As a result of this, the aluminium-rich components

charge for the duration of about a mintue. In this way impurities are removed from the metal to a much greater extent than was the case hitherto and the refining period is considerably shortened. This refining process has a beneficial influence on the heat-treatment stage, for when ordinary commercial magnesium is annealed without a sulphur-containing protective atmosphere it tends to oxidise and stain. This special refining also affects the hot-

TABLE I.—*Mechanical Properties of Cast Magnesium Alloys (Lay).*[1]

Type.*	Makers' marking.	Yield point, kg/mm.² 0·2 %.	Ultimate stress, kg./mm.²	Elongation per cent. ($l = 10\,d$).	Fatigue limit (bending), kg./mm.²	Brinell hardness 5/250/30, kg./mm.²
			(1) *Sand Castings.*			
G Mg-Al 6 Zn	AZG	9–11	16–20	3–6	7–8	50–60
G Mg-Al 4 Zn	AZF	8–9	17–22	5–9	5·5–7·5	45–55
G Mg-Al	A 9 V	10–11	24–27	8–12	8–10	56–63
G Mg-Si	CM Si	5–6·5	9–13	2–4		40–45
G Al-Si	Silumin	8·5–9	17–20	4–8	4–5	55–60
G Al-Mg-Si	Silumin Gamma	18–25	25–30	0·5–4	8–10	80–100
Cast iron	Machine castings	—	12		10–12	140–160
"	Machine castings (higher strength)	—	18		11–13	160–180
			(2) *Chill and Pressure Die Castings.*			
G Mg-Al	AZ 91	11–13	16–24	2–8	7–8	62–68
G Mg-Al	A 8	9–11	20–24	5–10	7–8	54–60

* The approximate compositions of the different types (DIN 1717) are given in THE METALLURGIST, February 25th, 1938, p. 98.

reappear even if the articles be allowed to cool slowly in the furnace after homogenising (Fig. 3).

The change in the mechanical properties of an alloy of the type G Mg-Al by such treatment is shown in the following table :—

	Yield point, kg./mm.².	Ultimate stress, kg./mm.².	Elongation, per cent.	Hardness, kg./mm.².
Untreated	8–10	16–20	3–6	50–60
Homogenised	10–12	23–28	8–12	55–65
Temper-hardened ...	14–16	25–28	3–6	70–75

The alloy is most frequently used in the homogenised condition. G Mg-Al 6 Zn (or called AZG) is used for components subjected to fatigue stresses and G Mg-Al 4 Zn (or called AZF) for components subject to impact stresses. The alloy Sg Mg-Al-Zn is used for pressure die castings and contains 9 per cent. aluminium and 1 per cent zinc ; it is suitable for difficult castings with light and thin walls.

A method of refining magnesium, worked out by Luschenowsky in very recent times, results in a marked improvement in properties. For example, in the case of alloys of the type G Mg-Al 6-Zn, the ultimate stress is raised by 1 to 2 kilos. per square millimetre, and the elongation 2 to 3 units per cent. compared with the usual commercial alloys. This improvement is not very big, but is remarkable as it is not due to any additional alloying elements or heat treatment, but solely to a greater purification of the raw magnesium and a special way of producing the alloys. Such test results were obtained from castings of varying form. An advantage of the cast alloys is that they do not require to be superheated. The method consists in melting down with the raw magnesium a salt mixture of chlorides and compounds which give off oxygen. Further, a special gas mixture is passed into the

rolling properties for, combined with a thermal treatment, a considerably higher rolling speed is obtained with alloys of the Mg-Al type ; further, the intermediate annealings are reduced. According to the literature, customary rolling speeds are low and in the neighbourhood of 30 m. per minute.

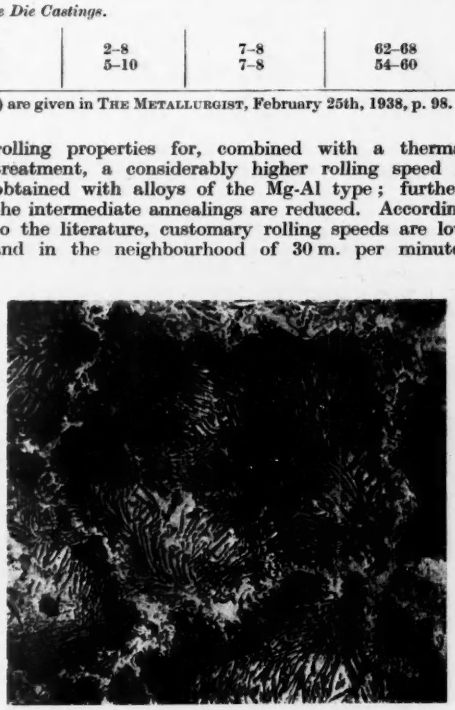

FIG. 3—*Temper-Hardened.*

Actually, rolling speeds of about 6 m. to 15 m. per minute are employed. In the case just mentioned, the rolling speed may be raised to 80 m. per minute, which results in an improvement in the properties. Given appropriate treatment, it is possible even to roll down from the ingot. Sheets prepared in this way may be still subsequently rolled up to 40 per

TABLE II.—*Mechanical Properties of Magnesium Alloys (Walberdorf).*[2]

Type.*	Makers' marking.	Elastic limit, 0·02%, kg./mm.²	Yield point, 0·2%, kg./mm.²	Ultimate stress, kg./mm.²	Elongation, per cent. ($l = 10\,d$).	Reduction of area, per cent.	Compression strength, kg./mm.²	Modulus of elasticity, kg./mm.²	Brinell hardness 5/250/30, kg./mm.²	Notched bar impact figure, mkg./cm.²	Shear strength, kg./mm.²	Fatigue limit (bending), kg./mm.²	Yield point in compression 0·2% kg./mm.²
						Sand Castings.							
G Mg-Al 6 Zn	AZG	4–5	9–10·5	16–20	3–6	5–7	33	4300	50–58	0·35	14	7–8	
G Mg-Al 4 Zn	AZF	4	8–9	17–21	5–9	9–11	32	4200	47–52	0·50	13	5·5–7·5	
G Mg-Al	A 9 V	4·5–5	10–11	24–27	8–12	8–15	31	4400	56–63	0·90	13–14	8–10	
G Mg-Al 3	AZ 31	3	5·0–6·5	16–20	7–10	12	29	4000	43–48	1·00	11	5–6·5	
G Mg-Si	CM Si	—	5·0–6·5	10–13	2·4	4–7	22	—	41–46	0·45	10–11	—	
G Mg-Mn	AM 503	—	3	9–11	3–6	5–9	17–18	—	35–39	1·10	8·5–9·5	—	
G Mg-Al	A 8 K	4·5	10–11	15–19	2–5	4–6	27–30	4300	52–57	0·25	12–13	7–8	—
						Press and Forging Alloys.							
Mg-Al 6	AZM	17–19	20–22	28–32	11–16	25–30	35–38	4500	60–65	1·00–1·40	14–16	13	12
Mg-Al 9	AZ 855	18–20	21–23	29–32	8–12	13–18	36–38	4500	68–75	0·60–0·80	14–16	13–14	12–20
Mg-Al 3	AZ 31	14–16	18–20	25–28	8–12	30–35	34–36	4300	53–58	1·00–1·40	13–15	10	10·5
	Z 1 b	9–13	16–18	25–27	15–18	25–30	34–36	4300	51–56	1·20	13–15	9	10·5
Mg-Mn	AM 503	8–10	14–17	19–23	1·5–5	5	30–32	4200	41–46	1·00	12–14	7	11·5
						Sheet.							
Mg-Mn	AM 503	5	8–14	19–23	5–10	—	—	3900	39–42	—	—	—	—

* The type to which each product belongs is inserted from information given by Lay.[1] The approximate compositions of the different types are given in THE METALLURGIST, February 25th, 1938, page 98.

cent., and if then soft-annealed are more plastic than the normal product.

The most important wrought alloys are given in Table II. The alloy Mg-Al 3 (or called AZ 31) may be easily worked and is suitable for etching purposes, decorative plates, &c. Mg-Al 6 (or called AZM) is a much-used general-purpose constructional alloy. It is used in such forms as rods, tubes, profiles, sheet, and die pressings, also in the forged condition. For parts which are subjected to higher stresses, such as airscrews and motor bearers, Mg-Al 9 (or called AZ 855) is used.

The strength properties of the alloys rise with increasing aluminium content. In the case of Mg-Al 9 the alloy may be used without any heat treatment at all, or in the homogenised and temper-hardened condition.

The magnesium-manganese alloys Mg-Mn 2 (or called AM 503) find very frequent application in the form of sheet for oil and fuel containers, cover sheeting, at the same time these alloys are easily welded and are the most corrosion resistant of the magnesium alloys.

The best conditions under which to hot-work magnesium alloys are usually provided by the producers. They are worked warm and up to a temperature of 300 deg. Cent. At present a magnesium-manganese alloy is being marketed which permits cold working within limits; for example, the sheet may be bent cold round a radius four times the sheet thickness.

Certain magnesium alloys tend to stress corrosion. However, the casting alloys, as well as the magnesium-manganese wrought alloys are free from this. The high-percentage magnesium-aluminium wrought alloys are more prone to the trouble, which can, however, be mitigated by heat treatment. The trouble can also be overcome by cladding with superficial layers of magnesium-manganese sheet which is corrosion resisting.

To increase the corrosion resistance of magnesium alloys they are treated with a nitric acid alkali-bichromate pickle. The best protection at the present time, especially against electrolytic influences, is the use of layers of varnish. A surface treatment making use of the oxide layer has also been improved very recently.

The greatest possible strength of the rolled and wrought alloys referred to above is about 28 to 32 kilos. per square millimetre. In the case of Mg-Al 9 the strength can be raised to 37 to 42 kilos. per square millimetre, as the result of thermal treatment (temper-hardening), but slight embrittling occurs as the elongation is reduced to 2 to 5 per cent. and the reduction in cross-sectional area to 3 to 6 per cent. In comparison, the heat-treatable aluminium alloys can reach strengths up to 50 or even 60 kilos. per square millimetre with sufficient elongation and toughness. Thus, if the wrought magnesium alloys are to find further application at the cost of aluminium alloys, then the strength must be raised without other properties suffering. Silver has been added to magnesium alloys in order to increase the strength. Laboratory experiments have shown increased strength on adding other metals without bad effects on the elongation and toughness. It is thus hoped to evolve valuable alloys somewhat similar to duralumin. Although the machineability of magnesium is very excellent indeed, yet experiments are in progress to improve this property still further with particular reference to automatic cutting machines.

Reference has been made to the great affinity of

magnesium and its alloys for oxygen, yet the danger of fire is absolutely negligible as far as the products of magnesium and its alloys (other than powder) are concerned. There is some danger in the machine shop if cutting tools are not sharp, in that friction may start a swarf fire; also if fine machine cuttings are stored in a wet condition or allowed to come into contact with substances capable of giving off oxygen. Given certain unfavourable conditions, dust containing magnesium in the form of very fine powder may give rise to an explosion. All these matters are not at all of a serious character, provided well-established precautions are adhered to.

A field of application for magnesium-base alloys is that of slide bearings, and research is now being done on this. It is possible for piston pins to run directly in Elektron pistons. Test bench results show that with Mg-Al 6 alloy (or called AZM) for alloy bushes and 60 mm. diameter pins with circulatory lubrication a speed of 3 m. per second at a bearing pressure of 250 kilos. per square centimetre may be attained. Such alloys are stated to be already on the market. These bearings must be kept in good working order.

In Germany every effort is being made to utilise magnesium and its alloys to replace other metals which have to be imported from abroad. This is being done with success as she possesses large quantities of the necessary raw materials. The German magnesium production is very large. It is a regulation there, for example, that magnesium be used for bus-bars for indoor switch installations carrying currents of about 600 amperes, and over. It also stipulates the use of magnesium components for parts of wireless receivers and telephone apparatus, also for fine mechanical and optical parts, tacheometers, and measuring instruments, &c.

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The Chromate Treatment of Zinc Alloys

As the result of the rapid technical developments of the last few years many new uses have been found for zinc-base alloys, especially in the form of die-castings, and at the same time the need has become evident for the protection of these zinc-rich materials against corrosion. Zinc itself owes its resistance to a very thin covering layer, consisting of hydroxide and hydrated basic carbonate, which forms in air and thickens in the presence of moisture. The artificial thickening of this natural layer suggests itself as a method of improving corrosion resistance, on analogy with the effective methods of intensifying the surface film which are already applied to aluminium. Zinc, like aluminium, is a metal whose oxide skin (according to Pilling and Bedworth) occupies a greater volume than the metal itself. The volume ratios are 1·24 for aluminium, 1·59 for zinc, but only 0·84 for magmesium. Favourable conditions for protective action of the oxide skin are therefore present in aluminium and zinc, although in the case of zinc the difference between the volume of the surface layer and of the metal is quite considerable, and a risk may be foreseen of the production of internal stress in the surface layer with consequent crack formation and poor adhesion in thick coatings.

A chromate process—known in America as the Cronak process—has been successfully operated for some years, mainly for the protection of zinc die-cast alloys. It is the object of some work described in a paper by H. Fischer and N. Budiloff[1] to make a further study of the significance and utility of this process for the surface treatment of zinc alloys. The method is analogous to the well-known chomate dipping process applied to magnesium alloys. The production of a surface layer is brought about by a short dip in an aqueous acid chromate solution. The zinc becomes covered with a greenish-yellow to yellow-brown film which consists chiefly of a difficultly soluble basic zinc chromate. Quantitative chemical analysis of the film has hitherto not been possible, but its original greenish colour seems to indicate that trivalent chromium, obtained by the reducing action of zinc on the hexavalent chromium, takes part in the formation.

The objects to be treated were degreased, either chemically in 40 per cent. caustic soda solution at room temperature, or electrolytically in a 4·5 per cent. solution of trisodium phosphate. They were thoroughly washed with cold water, then chromatised, and again washed in tap water. It was found that small changes in the concentration of acid (*e.g.*, between about 0·24 and 0·06 N) or of the oxidising chromium compound in the chromate bath, such as might occur during long use, were without marked influence on film formation, but changes in duration and temperature of treatment had much more effect on the quality of the protective layer. The copper-free die casting alloy of type Z3 (see table), after five seconds' immersion in a standard bath, has a light yellowish iridescent film, after ten seconds it has the colour of bright brass, and after thirty seconds it assumes a darker tint. With a dip of one minute the film begins to loosen and can be abraded by the finger. The colour also depends on the composition of the alloy, one with a copper content of 2·9 per cent. giving a greyish-green layer, while commercial zinc with 0·05 per cent. of lead gives a bronze colour. When there is segregation or lack of uniformity of the composition of the surface of an article there is corresponding irregularity of the colour of the film. The quality of the film is not affected by a rise of temperature of the bath to 45 deg. Cent., but when formed at 60 deg. Cent. the coating is flaky and can easily be rubbed off, whilst that formed at 80 deg. Cent. is loose and can be washed off. At the best the chromate film on zinc shows very little protection against mechanical wear. It can be dyed with organic dyestuffs, but the colours are not sufficiently fast to washing or light to have decorative value. The only useful property of the coating is to stop the chemical attack of zinc and zinc alloys.

In a dip in the chromate bath some zinc goes into solution, but the estimated reduction in thickness for a dip of fifteen seconds duration in a bath at 20 deg. Cent. is only 4 μ. The solution works very economically and a surface of 10 to 12 square metres of zinc can be protected per litre before the bath needs replenishing to bring it up to correct strength.

The effectiveness of the film was tested with the alloys indicated in the table, by placing specimens of surface area 24 to 42 square centimetres in beakers containing 300 c.c. of 3 per cent. sodium chloride solution at 20 deg. Cent. Small volumes of the solution were withdrawn at intervals and the zinc determined by means of the dithizone process,[2] whereby amounts of 0·001 mg. and upwards may be colorimetrically estimated. The zinc dissolved was

found to be directly proportional to the time. The attack continued to proceed at a constant rate indicated for the different alloys in the untreated and treated condition by the values given in the table. The attack was clearly hindered by the presence of the film, but the influence of the composition of the alloy was also evident as the protective action was much smaller on alloys of the higher range of copper content (2·5 to 2·9 per cent.).

Tests were carried out under more severe conditions, *e.g.*, salt spray tests extending over nine months, and immersion tests in 3 per cent. salt solution + 0·1 per cent. hydrogen peroxide; and these gave similar indications as to the absence of adequate protection in the chromate-treated copper-containing alloys. Unalloyed zinc, chromate treated, was found to give the best results, but in the presence of much copper the film was porous and ineffective. It is natural to consider the possibility of luting up the defects in the film by some subsequent treatment or of producing thicker films. Progress in this direction has been made, for example, by the New Jersey Zinc Company, but sufficient experience has already been obtained to indicate that with many compositions of zinc-base alloy chromate treatment is very effective.

TABLE.—*Effect of Chromate Treatment on the Amount of Zinc Dissolved in 3 Per Cent. Sodium Chloride Solution.*

Mark.	Composition, per cent.			Zinc dissolved in mg./cm.².			
	Al.	Cu.	Mg.	After 120 hours.		After 340 hours.	
				Untreated.	Treated.	Untreated.	Treated.
Z2	3·9–4·3	2·5–2·9	0·02–0·05	0·83	0·22	1·91	0·53
Z3	3·9–4·3	—	0·03–0·06	0·75	0·04	1·83	0·10
Z5	3·9–4·3	0·9–1·2	0·02–0·05	0·85	0·05	1·69	0·10
Z10	10	2	0·02–0·05	0·63	0·04	1·28	0·11

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Vector Diagrams of Complex Alloys

IT is often desirable in metallographic work to be able to represent alloys of complex composition graphically in a diagram. The use of the triangular diagram for ternary alloys, and of the tetrahedron for quaternary alloys is well known; and various devices have been employed for representing in a conventional way a greater number of variables. Professor Carl Benedicks has recently suggested a method of representing complex compositions such as those of the light alloys.* A semi-circular diagram is drawn containing a number of radii in easily distinguishable directions; for example, by dividing the semi-circle into eight equal parts, which gives nine different radii. Divisions along the length of a radius constitute a scale of composition, in Fig. 1 a linear scale. Each radius refers to one of the constituent elements—silicon, copper, zinc, magnesium, manganese, iron, and nickel. Any vector parallel to a given radius indicates the identity and amount of a constituent in the same way as a length along the radius itself. In the vector diagram (Fig. 1) the origin (or centre of the circle) represents pure aluminium. A binary alloy is represented by a point on the radius; thus "aluman," containing 1·5 per cent. of manganese in addition to aluminium, is represented by the point 1 on the manganese radius. A ternary alloy is represented by a radius-vector together with another vector parallel to one of the radii, both being measured according to the same scale. The alloy "peraluman," containing 2·2 per cent. of magnesium and 1·4 per cent. of manganese, illustrates this case (point 2). A quaternary alloy is given by a point reached by a succession of vectors, *i.e.*, one radius-vector and two others. This is shown by point 3, representing "anticorrodal," with silicon 2·0, manganese 0·7, and magnesium 0·65 per cent. An alloy with five constituents is located by a radius-vector and three vectors, parallel to other radii; *e.g.*, duralumin, containing copper 4·5, manganese 0·8, silicon 0·6, and magnesium 0·5 per cent.

This method of representation enables the contents of the different elements to be arranged in order of decreasing magnitude or in any other order that may be desired. The position of the point representing the alloy is independent of the order in which the vectors are drawn. When, however, the composition corresponding to a given point in the diagram is required, it is necessary first to trace back the series of vectors to the origin, and then starting from the origin to read off the numerical values of the successive vectors until the point is again reached. A point on the diagram has no definite meaning unless the succession of vectors which lead to it is clearly indicated.

In practice a logarithmic scale is to be preferred to a linear scale, and a scale like that in Fig. 2 enables contents from 0·1 to 100 per cent. to be represented; or by adding another modulus a scale which will show 0·01 to 100 per cent. can be obtained. All the radii need not refer to composition; they may be given any significance and numerical scale value desired. Thus in Fig. 2 the horizontal radius on the left is used for the values (limits) of Brinell hardness number of the alloy according to a linear scale. Fig. 2, which is redrawn from Professor Benedicks' diagram, includes most of, but not all, the alloys he refers to: points with an exterior circle indicate cast alloys. The diagram conforms with the ordinary classification of the light alloys according to the most important addition element. Thus the silicon-aluminium alloys are found on the silicon radius, the copper-aluminium on the copper radius, &c. The copper-aluminium alloy "lautal" (point 14) is characterised by an additional vector corresponding to 1 per cent. of silicon. There are two additional vectors (Mn, Mg) leading to point 7 (duralumin);

* *Comptes Rendus*, December 27th, 1938, Vol. 207, page 1398.

two also (Ni, Mg) to point 4 (" Y " alloy) ; and three (Mg, Si, Mn) to point 8 (superduralumin). The marks on the horizontal lines attached to the different points are intended to represent the upper and lower limits of the Brinell hardness of the corresponding alloys, according to the scale attached to the left horizontal radius.

There may be other applications of this type of two-dimensional diagram which can in effect be made to represent nine dimensions.

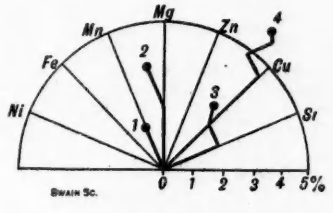

FIG. 1—*Linear Scale for Representing Compositions of Light Alloys.* 1, *Aluman* ; 2, *Peraluman* ; 3, *Anticorrodal* ; 4, *Duralumin.*

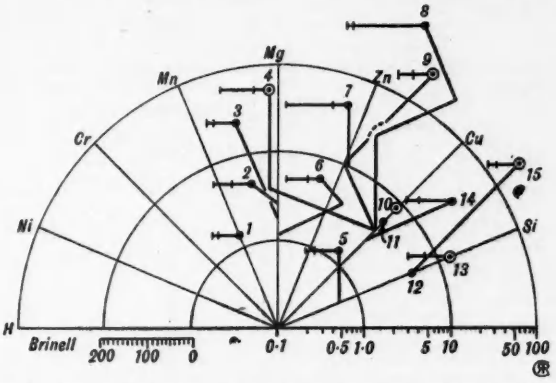

FIG. 2—*Logarithmic Scale for Representing Compositions of Light Alloys.* 1, *Aluman* ; 2, *Alcoa* 525 ; 3, *Hydronal* ; 4, " *Y* " *Alloy* ; 5, *Aldrey* ; 6, *Alcoa* 585 ; 7, *Duralumin* ; 8, *Superduralumin* ; 9, *Zinkal* ; 10, *American Alloy No.* 12 (8 *Per Cent. Copper*) ; 11, *Bahn-al* (6 *Per Cent. Copper*) ; 12, *Silicon Alloy* ; 13, *Silumin* ; 14, *Lautal* ; 15, *American Alloy* 108.

Chromium-Molybdenum Steels

INCREASED attention has lately been devoted in Germany to the chromium-molybdenum steels, and their properties have been extensively studied in comparison with those of steels containing nickel. At the instigation of the German Air Ministry, A. Pomp and M. Hempel[1] some time ago made comparative tests under similar conditions of twenty-one steels, some containing nickel and some free from nickel, with the object of assessing their suitability for use as high-tensile constructional materials. The steels were in the form of round bars, 80 mm. (just over 3in.) in diameter and about 1500 mm. (nearly 5ft.) long. They were treated to give tensile strengths in the range 90–100 kilos. or 120–130 kilos. per square millimetre (57–63·5 and 76–82·5 tons per square inch), and a systematic series of tests was applied to the product. These tests (of which complete results are given in the paper) included hardness tests along the length of the surface of the bar and throughout the cross section ; full tensile tests (with 0·02 and 0·2 per cent. proof loads) ; notched bar tests on two forms of test piece ; Wöhler alternating bend tests on specimens (*a*) polished, (*b*) with 60 deg. V notches, 0·1 mm. root radius, and 0·75 mm. deep, and (*c*) with an enlargement from 7·5 mm. to 12 mm. over a length of 15 mm.; and alternating torsion tests on polished specimens 14 mm. diameter, and on similar specimens bored with a hole 2 mm. diameter perpendicular to the stressed surface. Some figures indicating the mass effect in the steels examined are given in Table I. A number of case-hardening steels were included, but reference to these has been omitted. It was found that in the upper range of tensile strength (76–82·5 tons per square inch) steels containing 2·5 to 4·5 per cent. of nickel with additions of tungsten and molybdenum gave no better results in bars up to 3in. diameter than low nickel steels with additions of chromium, molyb-

TABLE I.—*Variation in Brinell Hardness over the Cross Section of 3in. diameter Bars of Various Steels (Pomp and Hempel).*

Steel Nos.	Type.	Average composition, per cent.						Maximum difference of hardness when tensile strength is—	
		C.	Ni.	Cr.	W.	Mo.	V.	76 to 82·5 tons per sq. inch.	57 to 63·5 tons per sq. inch.
1, 13	Ni-Cr-W ...	0·20	4·20	1·56	0·84	—	—	14	12
3, 14	Ni-Cr-Mo ...	0·29	2·77	1·25	—	0·40	—	11	11
4, 15	Ni-Cr-Mo ...	0·33	2·14	2·11	—	0·35	—	14	10
7	Ni-Cr-Mo-V ...	0·29	1·41	2·52	—	0·25	0·30	19	—
8, 16	Ni-Cr-Mo-V ...	0·23	1·22	2·49	—	0·28	0·21	28	25
10, 20	Cr-Mo	0·26	—	2·87	—	0·25	—	12	12
9, 18	Cr-Mo-V ...	0·43	—	1·53	—	0·31	0·26	22	15
12, 21	Mo	0·34	—	0·40	—	0·64	—	88	16
17, 19	Cr-Mo	0·38	—	0·98	—	0·27	—	—	28

denum, and vanadium. For tensile strengths of 57–63·5 tons per square inch, the nickel-free steels proved quite satisfactory. The chromium-molybdenum steels Nos. 10 and 20, containing a little under 3 per cent. of chromium, were specially promising in both ranges of tensile strength, and their properties as determined by Pomp and Hempel are given in Table II.

TABLE II.—*Mechanical Properties of 3 Per Cent. Chromium-molybdenum Steel Treated as 3in. Diameter Bar (Pomp and Hempel).*

	Steel No. 10.	Steel No. 20.
Composition, per cent.:		
Carbon	0·25	0·28
Chromium	2·95	2·78
Molybdenum	0·26	0·23
Nickel	0·31	0·13
Tensile tests :		
Yield point,[1] tons per sq. in.	63·7	50·5
Ultimate stress, tons per sq. in.	71·2	59·4
Elongation ($l=5\,d$), per cent.	16·5	21·1
Reduction of area, per cent.	51	69
Impact value, mkg. per sq. cm.:		
Large test piece[2]	14·1	19·1
German standard test piece[3]	7·2	11·3
Fatigue limit, tons per sq. in.:		
Wöhler[4], Polished	32·4	27·9
Notched[5]	16·1	17·3
With enlarged section[6]	24·8	20·3
Alternating torsion[7], Polished	13·8	14·4
Bored[8]	12·5	9·3

[1] 0·2 per cent. permanent extension.
[2] 15×22×160 mm. with 4 mm. diameter round notch, 7 mm. deep (15×15 mm. below the notch), 120 mm. between supports, 75 mkg. striking energy.
[3] 10×10×55 mm. with 2 mm. diameter notch, 3 mm. deep, 40 mm. between supports, 15 mkg. striking energy.
[4] Diameter 7·52 mm.
[5] 60 deg. V notch, root radius 0·1 mm., 0·75 mm. deep.
[6] With enlargement to 12 mm. diameter over a length 15 mm., radius 0·5 mm.
[7] Length 85 mm., diameter 14 mm.
[8] Bored with a hole 2 mm. diameter perpendicular to the stressed surface.

In continuation of this work A. Pomp and A. Krisch[2] have carried out tests on commercial specimens of six chromium-molybdenum steels of composition specified in Table III. The object of this investigation was to determine the degree of depth hardening, after heat treatment under various conditions, of specimens of different sizes. The information was obtained by means of hardness tests taken on the surface and throughout the cross section, and by tensile and notched bar tests on specimens from the outer zone and from the centre of the treated mass. These are given in full detail in the report. Table IV summarises the conclusions which may be drawn from the hardness measurements with reference to uniformity of hardening throughout thick sections of the oil-hardened and tempered steels. Eleven of the steels tested by Pomp and Hempel in the form of 80 mm. diameter bars fall within (or nearly within) the compositions specified in Table III, and the direct comparison which may thus be made between the two series of data affords useful confirmation of the results. The steels in question are :

Type of steel (Table IV).	Steels Nos. (Table I).
1454	17
1455	19
VCM0 240	9, 18
1456	10, 20
1460	4, 7, 8, 15, 16

While the low alloy compositions Nos. 1452/4/5 are limited in application to less than 3in. diameter, those with somewhat higher alloy content show good hardenability in the largest size studied, viz., 6in. Some typical properties in bars of this size are given in Table V. The factor for conversion of Brinell hardness (5 mm. ball, 750 kilos. load, 30 sec.) into tensile strength (kilogrammes per square millimetre) was determined statistically from a large number of measurements and was found to be 0·35 for all the steels except No. 1456; for this steel it was 0·34. These values reduced to tons per square inch are 0·222 and 0·216 respectively. No consistent variation of the factor with different tensile strength was observed in any one steel. E. Houdremont and H. Kallen[3], in a study of low alloy nickel-free steels, found a considerable mass effect in steel corresponding in composition to No. 1454. To aid in the development of special steels, having in mind the raw materials situation in Germany, E. Houdremont[4] investigated some 1 per cent. chromium-molybdenum steels and reported rather greater uniformity throughout the section than was found by Pomp and Krisch. In some cases, however, the tensile strength to which

TABLE IV.—*Depth Hardening Properties of Oil-hardened Chromium-Molybdenum Steels (Pomp and Krisch).*

Type of steel.	Tensile strength tons per sq. inch.	Maximum diameter for uniformity.	Maximum difference in hardness over cross section of this diameter.
Aircraft steel :			
1452	47·5 to 57	40 mm. (1·5in.)	11
	57 to 66·5	40 mm. (1·5in.)	34
1454	47·5 to 57	60 mm. (2·5in.)	16
	57 to 66·5	60 mm. (2·5in.)	26
1455	60 to 70	Between 60 mm. (2·5in.) and 90 mm. (3·5in.)	16 35
V-C-Mo 240	60 to 70	At least 150 mm. (6in.)	17
	70 to 80	130 mm. (5in.)	32
Aircraft steel :			
1456	60 to 70	At least 150 mm. (6in.)	15
	70 to 80	At least 130 mm. (5in.)	17
1460	60 to 70	At least 150 mm. (6in.)	14
	70 to 80	130 mm. (5in.)	26

TABLE III.—*Percentage Composition of Steels.*

Type.	C.	Si.	Mn.	S.	P.	Ni.	Cr.	Mo.	V.
Aircraft steel 1452	0·22–0·28	<0·35	<0·7	<0·015	<0·02	—	0·9–1·2	0·15–0·25	—
„ „ 1454	0·30–0·37	<0·35	0·5–0·8	<0·035	<0·035	—	0·9–1·2	0·15–0·25	—
„ „ 1455	0·38–0·45	<0·35	0·5–0·8	<0·035	<0·035	—	0·9–1·2	∼0·2	—
VC Mo 240	0·38–0·45	<0·35	0·5–0·8	<0·035	<0·035	—	1·6–1·9	0·3–0·4	∼0·2
Aircraft steel 1456	0·24–0·34	<0·4	0·4–0·8	<0·035	<0·035	—	2·3–2·7	0·2–0·35	0·2–0·35
„ „ 1460	0·24–0·35	<0·5	0·3–0·8	<0·035	<0·035	1·2–2·3	1·8–2·7	0·2–0·4	<0·25

the bar was treated was under 50 tons per square inch. A chromium-molybdenum-vanadium steel containing carbon 0·5, chromium 1·0, molybdenum 0·4, and vanadium 0·25 per cent., on the other hand, gave very little difference between outside and centre of a

seems to be in giving high tensile strength in medium or relatively small sections, while the 3·0 : 0·6 per cent. chromium-molybdenum and the 2·5 : 0·3 : 0·2 per cent. chromium-molybdenum-vanadium steels of the types discussed above offer the best alter-

TABLE V.—*Mechanical Properties of Chromium-molybdenum-vanadium Steels Heat Treated in the Form of 6in. Diameter bars to give a Tensile Strength of 60 to 70 Tons per Square inch (Pomp and Krisch).*

Type and make.		Composition, per cent.					Position of specimen.	Yield point,[1] tons/sq. in.	Ultimate stress, tons/sq. in.	Elongation,[2] per cent.	Reduction of area, per cent.	Impact figure,[3] mkg./sq. cm.
		C.	Ni.	Cr.	Mo.	V.						
V-C-Mo 240	I	0·42	—	1·67	0·39	0·19	Outside	54·8	65·6	16·8	62	10·5
							Centre	53·7	63·8	16·4	59	5·9
	II	0·40	—	1·80	0·36	0·19	Outside	56·6	66·4	16·6	59	7·8
							Centre	54·2	63·9	15·6	53	5·2
	III	0·39	—	1·78	0·30	0·15	Outside	59·3	68·6	15·5	55	6·2
							Centre	57·2	66·5	13·8	53	4·7
1456... ...	I	0·25	—	2·59	0·28	0·27	Outside	59·9	66·7	16·9	60	7·6
							Centre	57·9	65·1	15·8	60	7·5
	II	0·31	—	2·36	0·24	0·19	Outside	61·3	70·0	16·1	58	9·3
							Centre	59·4	67·8	14·9	56	5·6
	III	0·28	—	2·36	0·29	0·22	Outside	55·4	63·0	17·1	64	13·5
							Centre	52·8	60·1	16·8	63	9·5
1460... ...	I	0·28	1·53	2·46	0·23	0·09	Outside	61·1	67·5	16·9	64	8·5
							Centre	58·6	65·7	15·8	59	9·2
	II	0·35	2·27	1·85	0·38	—	Outside	56·6	66·5	18·2	64	13·1
							Centre	53·5	63·9	16·3	62	15·1
	III	0·32	2·19	2·23	0·30	0·16	Outside	55·1	64·5	18·7	66	16·1
							Centre	52·3	60·6	17·9	60	11·2

[1] 0·2 per cent. permanent extension.
[2] $l = 5d$.
[3] German standard test piece, 10 mm. by 10 mm. by 55 mm., with 2 mm. diameter notch, 3 mm. deep.

6in. diameter bar at a tensile strength of over 70 tons per square inch, with elongation 18 per cent. and impact figure 12 mkg. per square centimetre.

Apart from the steels containing a high percentage of nickel, the outstanding compositions in these series of tests appear to be the 3 per cent. chromium-molybdenum steel and the chromium-molybdenum-vanadium steels conforming to the specification 1456. The properties of the 3 per cent. chromium-molybdenum steel recorded by Pomp and Hempel have been given in Table II. Although details of treatment are not stated, the tensile tests clearly resemble those given by Swinden[5] for steel containing carbon 0·29, chromium 3·2, and molybdenum 0·6 per cent., oil hardened from 900 deg. Cent. in the form of 3½in. diameter bar and tempered at 600 and 650 deg. Cent. respectively. Dr. Swinden in the course of the paper referred to regards the development of 3 per cent. chromium-molybdenum steel as of great importance. It is a steel which shows a remarkably good combination and range of properties, and these are fully set out in Dr. Swinden's paper. The possibility of reducing the chromium and molybdenum content, provided that vanadium is added, is shown by the behaviour of steel 1456 (Tables IV and V) and a steel of this composition seems likely to possess very useful properties. It is more satisfactory than a low-nickel chromium-molybdenum steel containing no vanadium, though a nickel-chromium-molybdenum-vanadium steel of the type 1460 III is a possible alternative. This particular steel was about as good as 1456, but a comparison with the other two makes of 1460 (Table V) and with steels 7, 8, and 16 in Pomp and Hempel's series (Table I) indicates that for good properties in 6in. bars the carbon has to be kept up to about 0·3 and the nickel to well over 2 per cent. On the whole the field of utility for the type 1460 natives to nickel-chromium-molybdenum steel for material which has to be treated in large masses.

REFERENCES

[1] *Mitt. K.W. Inst. Eisenforschung*, 1937, 19, 221.
[2] *Ibid.*, 1938, 20, 103.
[3] Tech. Mitt. Krupp, 1934, 2, 117.
[4] *Stahl und Eisen*, 1937, 57, 480.
[5] " Trans., N.E. Coast Inst. Eng., 1938, 54, pages 221 and 219

Books and Publications

The Phase Rule and its Applications. By ALEXANDER FINDLAY. Eighth edition, revised with the assistance of A. N. CAMPBELL. Demy 8vo., pp. xv+327. 1938. London : Longmans, Green and Co. 12s. 6d.

THE application of the phase rule to alloy systems by Jüptner, by Le Chatelier, and by Roozeboom in the last years of the nineteenth century laid the foundation for the systematic presentation of the results of the study of alloys. In order to appreciate the work of Roberts-Austen on the iron-carbon diagram, of Heycock and Neville on non-ferrous alloys, and the contributions of Tammann and his co-workers, which were beginning to appear from the Göttingen laboratory, a study of the phase rule became a matter of considerable importance to metallurgists, and thirty-five years ago the first edition of this book provided them with the necessary guidance. With the development of metallography, a working knowledge of the phase rule has become not merely important, but essential to all metallurgists, and the latest edition of this well-known book will therefore be welcomed by them, as well as by chemists.

The general character of the book remains un-

changed. There has been no need for fundamental revision, but obsolete data have been replaced by more recent information, the bibliographical references have been brought up to date and the importance of X-ray analysis in the investigation of the nature of solid phases has been emphasised by frequent examples of the successful application of X-ray technique to phase-rule problems. In metallography, while thermal analysis and micrography retain their importance as standard methods of the study of the constitution of alloys, they are increasingly supplemented by other physical aids, and especially by X-ray analysis, as this method alone gives direct information on the most fundamental of all distinctions between two separate phases, viz., the difference in their space lattices.

In accordance with the original intention of the author, the exposition of the phase rule and its applications given in the book remains almost entirely non-mathemtical, the desire having been to explain as clearly as possible the principles underlying the phase rule and to illustrate their application to the classification and investigation of equilibria by means of a number of cases actually studied. The phase rule deals only with conditions of equilibrium and gives no information about the changes in equilibrium brought about by the alteration of external conditions of temperature and pressure. A feature of the last few editions, tending to extend the scope and practical utility of the book, has been retained in the discussion of the theorem of Le Chatelier and the detailed application of the Clausius-Clapeyron equation to a number of instances of the changes in the equilibrium brought about by alterations of pressure and temperature.

The strictly metallurgical part of the book is little changed from the previous edition. The different types of binary alloys are mentioned, but the main discussion is reserved for the iron-carbon diagram, for which the original $\delta-\gamma$ diagram of Ruer and Goerens (1916) is still given. Reference is also made to metallurgical subjects in dealing with ternary alloys, isothermal curves and space models though without discussion of specific up-to-date examples. The metallurgical applications are, in fact, only briefly dealt with, as is natural in a book dealing widely with the general subject of the phase rule—they must be found in specialised books on metallography, such as that by Dr. Desch in the same series—but no book could serve the metallurgist better for the study of the principles of the phase rule, illustrated by a great variety of examples drawn from a wide range of sources.

An Introduction to Metallurgy. By JOSEPH NEWTON. Med. 8vo, pp. ix+537. 1938. New York: John Wiley and Sons, Inc. London: Chapman and Hall, Ltd. 20s.

THE title of this work invites comparison with Roberts-Austen's famous "Introduction to the Study of Metallurgy," first published in 1890. Roberts-Austen then wrote: "The literature of metallurgy is rich, but those who are beginning to study it need guidance to a knowledge of the principles on which the art is rightly practised." This is the need recognised and provided for in Professor Newton's book, the compilation of which is governed throughout by the intention of giving to the student a comprehensive view of the field of metallurgy as a whole, and equipping him for understanding the specialised treatises on the various branches of metallurgy. The metallurgy of different metals is now dealt with to an increasing extent in different books separately and in detail. It is far more important at the outset for the student to know the scope of the subject, and to learn what foundation has been given to metallurgical practice in the past by the sciences of physics and chemistry, and what further aid may be expected in the future, than for him to acquire familiarity with the complicated details of processes and equipment. The book is divided into two parts dealing with what the author calls Part A: "Adaptive Metallurgy," and Part B: "Extractive Metallurgy." The scope of these divisions may perhaps be better understood from the contents of the chapters. In the first part are included an account of the structure and physical properties of metals and alloys; the shaping of metals and alloys (casting, mechanical working, &c.); the heat treatment of materials, ferrous and non-ferrous; and a brief summary of the industrial metals and alloys and their uses. The second part deals with minerals and ore dressing; hydrometallurgy (including cyaniding, &c.); pyrometallurgy (to which reference is made later electrometallurgy; sampling; and, corresponding to the last chapter of Part A, a brief account of the production of the industrial metals with data about supply and consumption in 1934. These concluding chapters in each part are not equal in value to the rest of the book, but are probably designed to lead the reader to seek fuller information from more specialised sources. The desirability of this course is emphasised throughout. The author likens his book to the skeleton, the specialised books to the flesh which clothes the bones, and current metallurgical literature to the life's blood of the study of metallurgy.

The book contains several notable features. In the first part equilibrium diagrams and the constitution of alloys are dealt with in considerable detail, and reference is made to some of the contributions of X-ray analysis to the study of metals and alloys. In the second part the underlying principles of "pyrometallurgy" are discussed at some length. Pyrometallurgy is defined as the branch of extractive metallurgy that involves chemical reactions brought about by means of heat supplied by the burning of fuel. The chapters devoted to this subject comprise nearly one-third of the book and include an elementary thermodynamical treatment (too often lacking in metallurgical text books) of free energy and entropy changes, chemical equilibrium and thermochemistry; and sections on pyrometry, fuels and refractories, slags and fluxes, typical metallurgical processes and plant. The machines, furnaces and equipment illustrated are mainly American, and in the descriptive matter American practice takes the first place. Each chapter concludes with a few straightforward exercises designed to test the reader's understanding of the basic principles involved. Answers to the numerical problems would have been an aid to the student. It is true that the data necessary for the specific problems are not always given in the text and must be obtained from other sources, but the approximate results of the calculations based on standard data would be a great assistance in enabling the student to check the accuracy of his own work. A useful bibliography at the end of each chapter and numerous footnotes in the text serve to direct the reader to standard sources of information on the topics discussed.

This is essentially a book for students, and should prove to be of great value to those who are preparing to profit by more advanced courses in various branches of metallurgy.